Available online at www.sciencedirect.com
SCIENCE DIRECT
Renewable and Sustainable Energy Reviews
8 (2004) 401–431
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

# Sustainable small-scale CHP technologies for buildings: the basis for multi-perspective decision-making

Kari Alanne *, Arto Saari

*Laboratory of Construction Economics and Management, Helsinki University of Technology, P.O. Box 2100, 02015 HUT, Finland*

Received 13 January 2003; accepted 17 December 2003

**Abstract**

Generally speaking, the concept "small-scale CHP" (combined heat and power) means combined heat and power generation systems with electrical power less than 200 kW. The significant benefit of CHP is its overall efficiency, which can be as much as 85–90%. One of the most promising targets in the application of CHP lies in energy production for buildings. The most important competing technologies in this regard are reciprocating engines, micro-turbines, Stirling engines, and fuel cells. The benefit of these technologies is their ability to utilize sustainable fuels, like regenerative biomass, which makes them attractive. In spite of many technical and economic obstacles limiting the availability and feasibility of these technologies at the moment, the literature is optimistic about their future. The breakthrough of new technology is often regarded simply as a matter of decision-making.

This article is a general review of issues that can be supposed to influence decisions when considering small-scale CHP as an alternative energy source for buildings. Firstly, a brief review is presented concerning the political, economic, social, and technological environment of small-scale energy production. Obstacles limiting the market potential of the new technologies are then listed, and solutions are suggested to improve their potential in Europe's liberalizing energy market. The relevant interest groups influencing decisions both for and against the introduction of the new technologies, as well as their status are recognized. Finally, the advantages and disadvantages of relevant small-scale CHP technologies are briefly discussed, with respect to building energy generation. Finland's role in this study is emphasized, but the international perspective is also dealt with.


* Corresponding author. Tel.: +358-50-4680892.
*E-mail address:* kalanne@iki.fi (K. Alanne).

1364-0321/$ - see front matter 
doi:10.1016/j.rser.2003.12.005

*Keywords:* Distributed energy systems; Buildings; Decision-making; Interest groups

**Contents**



## 1. Introduction

Combined heat and power (CHP), also known as cogeneration, means that both electrical and thermal energy are generated simultaneously. The significant benefit is the overall efficiency, which can be as much as 85–90%. If only electricity is produced, an efficiency of only 40–45% can be achieved. Thus, CHP can be regarded as an efficient way to produce energy. Conventionally, CHP plants have been large-sized, centralized units. Steam and heat produced by these plants can be utilized in industrial processes and district heating, provided that the steam temperature is high enough [1]. In the Finnish energy infrastructure, CHP plays a significant role. In 1998, 33% of Finland's electricity was produced by cogeneration [2]. In 2001, the proportion was almost 40% [1].

A new trend is towards distributed CHP, which means that the energy production unit is situated close to energy consumers and large-sized, centralized units are substituted by smaller ones. If the electrical power produced by the plant is less than 200 or 100 kW, the terms small-scale distributed CHP and micro-CHP are used, respectively. One of the most promising targets in the application of CHP lies in energy production for buildings. The relevant competing technologies in this regard are reciprocating engines, micro-turbines, Stirling engines, and fuel cells. In the smallest size, fuel cells and Stirling engines are regarded as the most applicable technologies. The benefit of these technologies is their ability to utilize sustainable fuels, like regenerative biomass, which makes them environmentally friendly. From the point of view of sustainability, fuel cells are almost transcendent [3].

The new technology has already been brought nearer to private energy consumers as a consequence of several technological advances. In spite of many technical and economic obstacles limiting the availability and feasibility of these technologies at the moment, the literature is optimistic about their future [4]. The breakthrough of new technology is often regarded simply as a matter of decision-making. For example, according to Dunn [5], an argument has been presented about hydrogen economy: “If we really decided that we wanted a clean hydrogen economy, we could have it by 2010”.

This article is a general review of issues that can be supposed to influence decisions when considering sustainable small-scale CHP as an alternative energy source for buildings. The existing literature dealing with this field of research is somewhat fragmental and usually concerns these issues in quite a one-sided way. Thus, the need has been recognized for collecting basic research information in one framework instead of as single case analyses. In the final analysis, the decision to support this new technology rests with the interest groups, ranging from political decision-makers to real estate owners, based on the broader interest of sustainable development. Probably because of the novelty of the technology in this field of application, the role of different interest groups in this context has not been a very popular subject of research in earlier studies. Thus, this aspect is emphasized in this article.

This study is a literature research by nature. The first information search was based on a large number of references found via the Internet. The scientific database “ScienceDirect” was utilized. First, the most important publications were found, namely the ones containing the newest (published 1995 or later), most interesting articles concerning energy decision-making. These articles were examined in greater detail and with a critical eye. The study thus contains 32 articles from 17 journals as well as four conference articles, three other research reports, and a computer software manual. In addition, some literature dealing with Finnish political definitions and regulations were included as well as information about the strategies of various companies manufacturing CHP devices.

In the first part of this article, a brief review is presented concerning the political, economic, social, and technological environment of small-scale energy production. Obstacles limiting the market potential of the new technologies are then listed, and

solutions are suggested to improve their potential on Europe's liberalizing energy market. The second part concerns the interrelatedness of human beings and nature, which directly impacts any decision regarding the introduction of new technologies in buildings. These groups, their human needs, demands and requirements, as well as their inherent role in the decision-making process have been considered. Finally, the advantages and disadvantages of relevant small-scale CHP technologies are briefly discussed, with respect to building energy generation. Finland's role in this study is emphasized, but the international perspectives are also dealt with.

## 2. Operational environment of small-scale CHP

### *2.1. Factors affecting the operational environment*

The market opportunities of new technologies depend strongly on the operational environment, which usually has been regarded as an entity consisting of political, economic, social, and technological factors (the so-called PEST factors). The review presented in this chapter is based on the traditional PEST classification.

In the literature, an extensive range of PEST factors has been presented that can be assumed to affect the operational environment of energy production. Some of the PEST factors have been listed in Table 1. In the traditional PEST classification,

Table 1
Operational environment of energy generation [4, 6–8]

| Political environment | Economic environment | Social environment | Technological environment |
|---|---|---|---|
| Taxation policy | Standard of living | Population structure | Natural conditions |
| Legislation and regulations | Energy consumption infrastructure | Distribution of incomes | Availability of electricity and fuels |
| International agreements (Kyoto Agreement) | Energy production infrastructure | Life style | Existing technologies and their features |
| Political stability of society | Purchasing power | Opinions on "green" issues | New technologies and their features |
| Political and strategic definitions at the national and international level (emission trade, attitude to nuclear power) | Economic development | Awareness of new technologies and their possibilities | Rate of technological development |
| Governmental support (taxes, subsidies, etc.) | Interest rates | Standard of education | |
| | Inflation | Traditions | |
| | Price of energy, fuel and technology | | |
| | Location | | |
| | Organizations operating on the market | | |
| | Libreralization of energy market | | |

the role of environmental issues is not always clearly defined, which can be regarded as a deficiency.

### 2.2. Obstacles limiting the market of small-scale distributed CHP

The leading hypothesis of this article is that technology and energy should be available at a competitive price, and a sufficient amount of reliable information should be available, before a decision-maker (for example, a real estate owner) will be ready to make a decision leading to investment in a new small-scale CHP technology.

It is well known that the existing fuel infrastructure is mainly based on fossil fuels. As a consequence, the availability of sustainable fuels is limited. Together with the rather high price of technology at the moment, this seems to be the most significant techno-economic obstacle limiting the breakthrough of sustainable distributed small-scale CHP technologies [4].

The liberalization of the electricity market tends to lead to a decline in the price of electricity, which does not necessarily make small-scale CHP attractive. On the other hand, however, the liberalization of electricity markets has caused poor electricity price predictability in the long run. This in turn diminishes interest in new, large-scale plant investments, thus opening new opportunities for small-scale CHP [3].

According to the literature, it is quite obvious that the support of the public administration plays an important role when new small-scale CHP technologies are to be introduced in the market. This support can be in the form of investment subsidies, tax subsidies and regulations as well as in terms of flexible bureaucracy and favorable political and strategic definitions. Most of the promises concerning governmental support, however, have not come into practice yet [8].

In this study, we argue that the human being himself is an important obstacle limiting the breakthrough of sustainable small-scale CHP technologies. Lack of interest in CHP can be seen a consequence of lack of confidence in CHP, which can be regarded as an obvious consequence of lack of information about the real benefits of CHP. In the literature, obstacles have also been mentioned concerning the integration of small-scale CHP into buildings. These problems, however, are studied in many other research projects and thus they are not dealt with in this study in detail. Some of these previously mentioned obstacles have been listed in Table 2, using the PEST classification described in Section 2.1.

### 2.3. Improving the situation

It is obvious that change is required both on the techno-economic side and that related to attitudes before small-scale CHP can become part of our everyday life. There is still a lot to do to develop technological solutions. Especially, modularity and integration of CHP into building energy systems should be improved. At the moment, research in this area has reached the practical phase and results can only be achieved on the basis of numerous field tests and operational experience.

Another significant improvement potential lies in the expectation of gradual changes in the existing fuel infrastructure. Today, natural gas is regarded as the

Table 2
Obstacles to small-scale CHP [8]

| | Obstacle |
|---|---|
| Technical obstacles | Missing connection to gas network |
| | No other usable fuels available |
| | Lack of space in the existing building |
| | Unfavorable temperatures |
| | No adaptability to part load operation |
| | Lack of standardization of CHP modules |
| Economic obstacles | Too low buy-back rates |
| | Too high electricity production costs |
| | Lack of funds for the investments |
| | High price of the technology |
| Political obstacles | No means of obligating utilities to cooperate |
| | Only short term investment subsidies available |
| | Inflexible and slow bureaucracy |
| | Unfavorable political and strategic definitions (e.g. nuclear power) |
| Social obstacles | Lack of confidence in technology |
| | Lack of information and ignorance of real benefits of CHP |
| | Lack of skilled personnel |
| | Co-operation problems with the utilities |

most applicable fuel for small-scale, distributed CHP technologies. The problem is the demand for an extensive natural gas distribution network. One of the most interesting and important features of CHP technologies is, however, their ability to utilize various fuels. To improve the status of small-scale CHP in the market, this flexibility should be utilized. Considering a retrofit of the energy system of an oil-heated building as an example, the technical infrastructure demanded by the oil heating system can be effectively utilized by using oil as a fuel for CHP at the beginning. When new alternative fuels like methanol are available, the existing infrastructure can be obviously used without major changes.

Further details about sustainable fuel infrastructures can be found in the articles written by Dunn [5] and Paine et al. [9]. Traditionally, non-stationary applications like vehicles have been regarded as an important market area for small-scale CHP devices. According to Gacciola et al. [10], the technological development of fuel cells for portable and transport applications can also be seen as an incentive for a new fuel market infrastructure. Some practical means to improve the market of CHP, suggested by the literature, have been listed in Table 3.

It is obvious that an improvement in the market opportunities for small-scale CHP will take time. This is illustrated, for example by Vartiainen et al. [4] in a market study for Finland. In that study, changes in the operational environment have been taken into account on the basis of three time periods: short term (until the year 2005), medium term (2005–2010) and long term (2010–2020). Vartiainen et al. [4] argue that existing structures will mainly dominate in the short term,

Table 3
Possible solutions to problems constraining diffusion of small-scale CHP [8]

| | Solution |
|---|---|
| Technological solutions | Improving the utilization of waste heat (e.g. cooling energy)<br>Development of modularity and improved integration into building energy system<br>New technological solutions |
| Economic solutions | Increasing and intensifying marketing<br>Optimization of heat and electricity tariff usage<br>Increased demand of energy<br>Rental and leasing activity |
| Political solutions | Updating legislation and regulations |
| Social solutions | Intercessors between the energy producer and the utility<br>Increasing communication and standardization<br>inculcation of enlightened attitudes through education |

whereas changes will be possible in the medium term. Changes in human values and attitudes seem to be the slowest. The idea is illustrated in Table 4.

Sometimes, it is possible for these changes to take place sooner than is anticipated by Vartiainen et al. [4]. A major factor impacting the political and economic climate in recent years was the terror attack of September 11, 2001, in New York followed by "The War Against Terrorism". The threat of Middle Eastern terrorism has contributed to the disincentive as a kind of "shock therapy" for the oil-dependent industrialized countries building large-scale centralized plants based on fossil

Table 4
Possible changes in operational environment in different periods [4]

| Environment | Short term | Medium term | Long term |
|---|---|---|---|
| Political | Existing political and strategic definitions | New political and strategic definitions<br>Effects of international agreements (Kyoto) become noticeable | Changes in structures of the society |
| Economic | Existing energy infrastructure | Changes in energy infrastructure (demand, supply and substitution effects) | Significant changes in energy infrastructure |
| | Existing actors (utilities, technology suppliers, etc.) | New actors, changes in competition situation | |
| Social | Existing values and attitudes | In general, existing values and attitudes | Changes in values and attitudes |
| Technological | Existing technological solutions<br>Existing networks (fuel, etc.) | New technological solutions and improvement of existing solutions<br>Existing networks become more extensive | Completely new energy technological solutions |

fuels [11]. The Prestige oil spill is another example of an incident that can rapidly change public perceptions, attitudes and in turn the temper of the times. The European Commission, however, has not yet changed its energy policy towards a more sustainable direction because of that accident [12]. In Nordic countries and other countries where hydropower plays an important role as a source of electricity, natural conditions (e.g. lack of rainwater, frosts) can dramatically affect the availability of electricity and thus impact its price within a short period of time [13].

In this study, we argue that the possibilities of sustainable CHP technologies in the market could be improved significantly by delivering reliable and illustrative information about CHP technology to the right people at the right moment. This is an obvious consequence for two reasons. Firstly, changes in public attitudes are slow to occur. Secondly, they have a strong effect on other limiting factors, either directly or indirectly. It is well known, however, that human beings cannot be obliged to change their behavior. The only way seems to be to influence attitudes gradually through education. Roughly, the change in attitudes should occur in two phases. In the first phase, public administration should be convinced about CHP, when they are in the process of defining energy policy and laws. The status of public administration as an opinion-former could then be utilized in the most effective way. In the second phase, when the new technology is penetrating the market in the form of new products, individual real estate owners as well as designers should be equipped with an adequate amount of reliable information about sustainable CHP technology.

## 3. Different interest groups, their roles and preferences in energy decision-making

### 3.1. General

It is obvious that a lot of decisions have to be made by various decision-makers before a real estate owner can be assumed to be ready to invest in new, sustainable small-scale CHP technology in a building. In this section, the relevant interest groups and their roles and preferences in this large decision-making scenario are discussed. Carefully studying the literature, we have first recognized the interest groups the attitudes and requirements of which can affect the decisions in this decision-making scenario. The roles of these interest groups in the operational environment have also been recognized as well as the most important decision-making problems. The roles and decision-making problems have then been classified into five categories and are listed in Table 5. We emphasize that the roles in the decision-making process are a consequence of the roles in the operational environment and thus they should be separated in order to avoid confusion.

According to the definition by the World Commission on Environment and Development [14], sustainable development is regarded as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Though costs have usually been the only criterion when selecting technological solutions for buildings, the definition of sustainability

Table 5
Roles and decision-making problems

| Roles | Decision-making problems |
| --- | --- |
| *Political roles* (1) | *Political and strategic decisions* (1) |
| Policymaker (11) | Selection of policy (11) |
| Legislator (12) | Selection of strategy (12) |
| Regulatory supervisor (13) | |
| *Administrative roles* (2) | *Economic intervener decisions* (2) |
| Administrative person (21) | Pricing (21) |
| | Selection of terms of insurance (22) |
| | Investment decision (yes/no)(23) |
| | Loan allowance (yes/no)(24) |
| | Transportation problem (25) |
| *Economic roles* (3) | *Project-based decisions* (3) |
| Financier (31) | Scheduling problem (31) |
| Equity/capitalist (32) | Selection of companies (deliverer, contractor, utility) (32) |
| Competitive actor (33) | Selection of action plan (33) |
| Trader or marketer (34) | |
| Risk manager (35) | |
| *Socio-environmental roles* (4) | *Selection of spatial solutions* (4) |
| Owner (41) | Selection of location (siting problem)(41) |
| Occupant (42) | Selection of layout (42) |
| Worker (43) | *Selection of technical solutions* (5) |
| Employer (44) | Selection of materials (51) |
| The public at large (45) | Selection of structural system (52) |
| Trade promoter (46) | Selection of sources of energy (53) |
| Culture promoter (47) | Selection of HVAC system (54) |
| Welfare promoter (48) | Selection of information system (55) |
| Promoter of environmental issues (49) | Selection of design parameters (56) |
| Informant (410) | Selection of functional mode (57) |
| Life supporter (411) | |
| *Technological roles* (5) | |
| Project planner (51) | |
| Designer (52) | |
| Expert (53) | |
| Supporting actor (55) | |
| Constructor (56) | |

should not be ignored in the larger context. The needs and demands of human beings and the environment obviously affect the attitudes behind the decisions. The decisions, in turn, obviously affect the costs, for example in the form of political definitions. In this study, the preferences of human beings and the environment have thus been assessed with respect to sustainability indicators. A list of sustainability indicators for the evaluation of buildings and their systems has been presented, for example, by Häkkinen et al. [15]. The information associated with the sustainability indicators can be utilized in many contexts, for example in the multicriteria evaluation of various technological solutions, as described by Andresen [16]. That kind of case analysis of energy systems is presented, for example, by Soebarto et al. [17] and Carlson [18].

In this study, the role of a real estate owner as the final decision-maker is emphasized. Thus, our departure point is the consideration of the interest groups directly associated with a building, then widening to the broad generic concept of the whole balance of nature, as illustrated in Fig. 1. As was argued in the previous

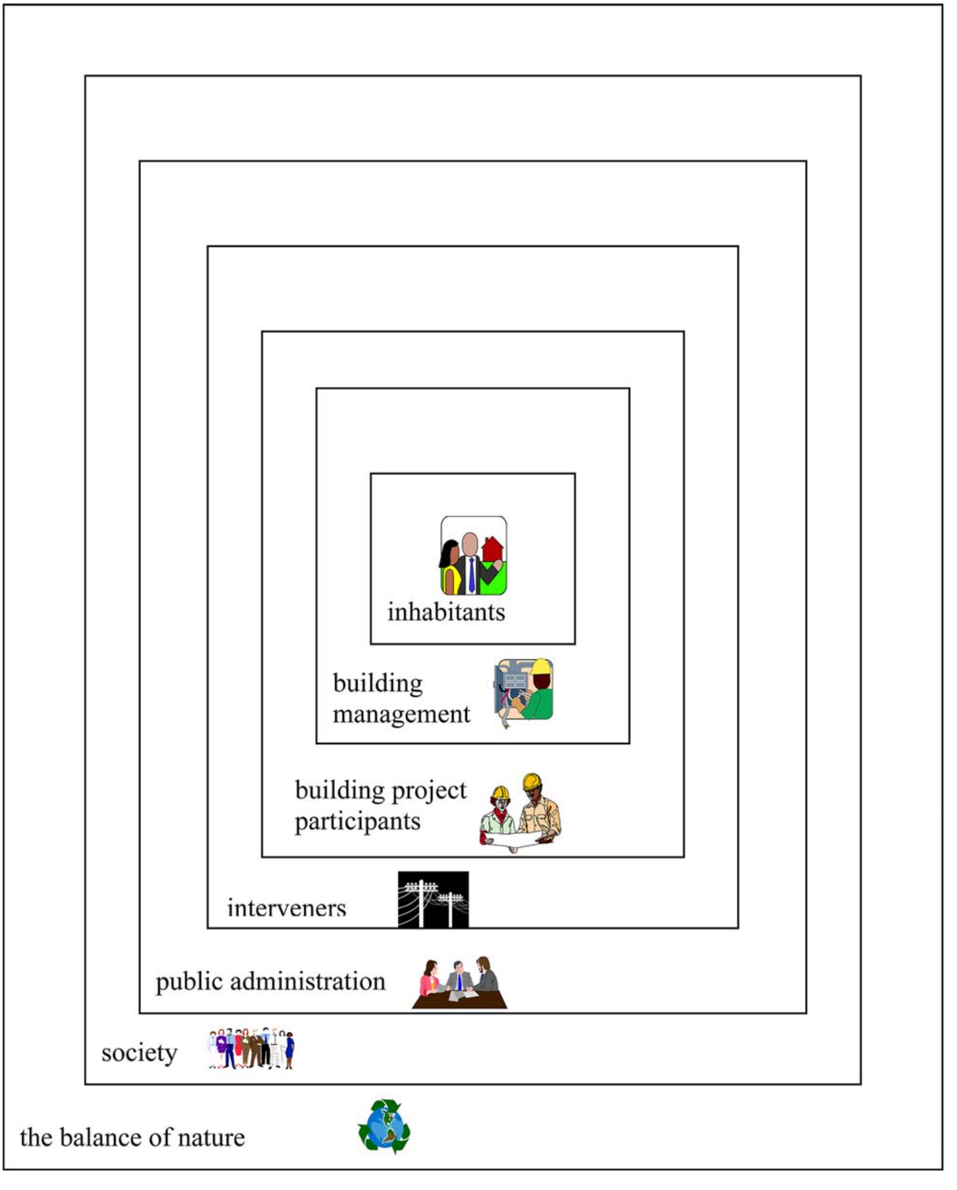



Fig. 1. Main interest groups.

chapter, change in attitudes can be regarded to happen in two phases. In the first phase, public administration should be convinced about CHP. In the second phase, the individual real estate owners as well as designers should be equipped with an adequate amount of reliable information about sustainable CHP technology. Thus, some weight has been given to these interest groups.

### 3.2. Inhabitants

Inhabitants can be simply regarded as people permanently or temporarily living in a certain place, for example in a building. The role of inhabitants in decision-making is associated with their economic responsibility as well as with their responsibility for real estate management. Thus, the inhabitants can be roughly classified into two categories. Referring to Table 5, a more detailed description concerning inhabitants as a part of the operational environment has been presented in Table 6.

The first category is "inhabitants with weak or indirect economic interest or no economic interest at all". For example, tenants [19] and occupational personnel [20] can be regarded as members of the first category. It is reasonable to assume that the degree of direct participation of these groups in decision-making concerning small-scale CHP is limited. As occupants, however, they usually have to carry the consequences of bad decisions, for example by paying too high a rent, suffering from uncomfortable working conditions with noise and odors [20], or being exposed to electricity blackouts or even safety risks [21]. As a consequence, they can make a decision to change the apartment or employer. Thus, they indirectly affect the decision-making of a real estate owner. When making decisions to invest in new technology, one of the objectives should be that changes with respect both to the rent charges and safety and comfort conditions—if the situation cannot be improved—at least should be kept minimal. Because there is usually an obvious need to increase rent level after a technology investment, the occupants should be informed about the advantages of new technology.

Table 6
Roles and DM problems of inhabitants

| Interest group | Role | DM Problem type |
|---|---|---|
| Inhabitants with no (or weak indirect) economic interest | | |
| Periodical occupants (occupational personnel) | 43 | No decisive role |
| Continuous occupants (tenants, patients in hospital, etc.) | 41, 43 | No decisive role |
| Inhabitants with economic interest | | |
| House builders | 31, 41, 42, 51, 55, 56 | 23, 31, 32, 33, 41, 42, 51, 52, 53, 54, 55, 57 |
| Owners of existing buildings | 41, 42, 55 | 23, 31, 32, 33, 51, 52, 53, 54, 55, 57 |

The second category is "inhabitants with economic interest". In practice, that means resident owners. In other words, they are people living in a building who either own the whole building (detached house) or part of it (condominium). As final decision-makers, the importance of resident owners should be emphasized. The most important decision-making problem faced by this interest group concerning small-scale CHP is whether to invest in new sustainable technology or not. Because of the economic responsibility of a resident owner during the construction, operation and demolition of the system, life-cycle costs can be regarded as the most important aspect, in addition to typical requirements of an occupant as presented previously. Therefore, a need has been recognized to carefully study the effects of small-scale CHP technology advancements on the life-cycle costs of buildings.

According to the synthesis made on the basis of references [22–32], we would additionally like to emphasize the importance of the concept of functionality in the decision-making of a single resident owner. The concept of functionality is usually mentioned in the literature when describing how well a product suits the purpose for which it is intended. Functionality is also usually defined by means of sustainability indicators, thus being well associated with sustainable development.

In the context of small-scale CHP, functionality firstly means flexibility in respect of resources. The ability of CHP technologies to utilize various fuels can be seen as an example of flexibility. On the other hand, as a requirement, flexibility means that spaces and the location of the building should be utilized as effectively as possible. In the case of CHP, for example one should be able to utilize the existing technological infrastructure (for example, existing oil tanks) without major changes.

A resident owner also has the responsibility for maintenance and operation of the system. In this context, the concept of "functionality" can also be used to describe the maintainability and reliability of a system. The CHP technology should thus always be assessed with respect to its service life and risk of damage. The implementation and operation of new technology should be as easy as possible. Unfortunately, when introducing new technology, special services (e.g. expertise) are usually needed. These services should be available locally at a competitive price.

The importance of functionality from the point of view of resident owners is supported by Riihimäki et al. [32], who present a Finnish study dealing with the attitudes of families planning a detached house. The study can be seen as an indication of change towards "soft" values. Traditional aspects like low maintenance, energy and construction costs were surprisingly not highly appreciated by the object group. As a consequence, there is a better chance of influencing the essential positive attitudes needed for introducing new technologies. Regardless of the importance of the inhabitants' point of view, however, their role in the short term is not critical from the point of view of small-scale CHP because the technology is not yet readily available on the market.

### 3.3. Building management

In general, the concept ''building management'' means a professional approach to owning and maintaining a building. Firstly, it is regarded as the operation of professional staff maintaining and providing services for that building. These kinds of building professionals are real estate managers and janitorial services. Secondly, it means real estate owners, in the context of companies owning several buildings and having their own business administration with internal decision and policy making as well as energy and economic planning. Referring to Table 5, a more detailed description concerning building management as a part of the operational environment has been presented in Table 7.

We assume that the degree of direct participation of building professionals in decision-making concerning small-scale CHP is usually limited. As supporters, however, they have to carry the consequences of bad decisions, for example by paying for the extra education, making several additional visits to the building, suffering from uncomfortable working conditions with noise and odors, or being exposed to safety risks. They can indirectly affect the decision-making of a real estate owner like inhabitants without economic responsibility. Because of their professional view and experience, however, every decision concerning small-scale CHP in buildings should always be made taking into account their opinions. Thus, their role in the decision-making is quite obviously more important than the role of inhabitants without economic responsibility.

The role of a real estate owner itself in the decision-making process is essential and various decision-making problems can be recognized. In addition to private resident owners' decisions, real estate owners may have to select company strategies and policies as well as deal with pricing problems (rents). The real estate owner also plays a role in sales and marketing the products, i.e. apartments.

As a company, profitability (usually measured in terms of return on investment) can be regarded as the most important preference of real estate owners. Because the costs during the lifetime of a building significantly affect the profitability, life-cycle studies can also be recommended from this point of view. According to the synthesis made on the basis of references [33–40], we would like to emphasize the importance of the aspect of competitiveness in the decision-making of a real estate

Table 7
Roles and DM problems of building management

| Interest group | Role | DM Problem type |
| --- | --- | --- |
| Real estate owner | | |
| Internal decision- and policy makers | 11, 34 | 11, 12, 21, 23, 31, 32, 33, 41, 42, 51, 52, 53, 54, 55, 57 |
| Energy and economy planners/analysts/ engineers | 11, 51 | 12, 25, 31, 32, 33, 53, 57 |
| Building professionals | | |
| Real estate managers | 21, 53, 55 | No decisive role |
| Janitorial service | 43, 53, 55 | No decisive role |

owner. Competitiveness can be regarded as a sum of company image and quality of the products. The occupants' preferences described in Section 3.1 are thus also preferences of a real estate owner. The strategic point of view seems to lead to the increasing need for also taking into account environmental values. A real estate owner investing in new sustainable small-scale CHP technologies, can obviously improve the company image by emphasizing the environmental value of the new technologies as well as their novelty value.

A case study is presented by Huovila et al. [33] about the preferences of an owner of a nursery school towards sustainable construction. On the basis of the study, the most important preferences were low investment costs, good environmental value, good comfort, and safety. Low maintenance costs and good functionality were not primary concerns. In general, the real estate owner's commitment to sustainable construction mainly arose in terms of environmental value and comfort. In conclusion, the environmental value should be emphasized in this case, when describing the benefits of the new technology to a real estate owner. It is obvious, however, that the role of real estate owners in decision-making will not be critical before the new technologies are widely introduced.

### 3.4. Building project participants

The interest group ‘‘building project participants’’ usually consists of a design group (including at least an architect, an HVAC engineer, an electricity engineer and a structural engineer), a real estate owner (a client) and a contractor. Because decisions concerning building design are mainly made by this group of people, it also plays an important role when considering small-scale CHP technologies as an energy source for a building. Referring to Table 5, a more detailed description concerning building project participants as a part of the operational environment has been presented in Table 8.

The possibilities of a contractor to affect the final decision concerning small-scale CHP are also quite limited. Their role and interests in the decision-making can be regarded as quite similar to those of building professionals, as was discussed in Section 3.2. However, because they represent the constructor in the group of building project participants, their opinion may be somewhat more important than that of building professionals.

Table 8
Roles and DM problems of project participants

| Interest group | Role | DM Problem type |
|---|---|---|
| Project planners (design team) | | |
| Architects | 51, 52, 53 | 21, 31, 32, 33, 42, 51, 52, 54, 56 |
| HVAC engineers | 52, 53 | 21, 42, 51, 54, 56, 57 |
| Electricity engineers | 52, 53 | 21, 42, 51, 55, 56, 57 |
| Real estate owners | 51 | See previous |
| Contractors | 56, 43 | No decisive role |

Because the role of contractors in decision-making process cannot be regarded as very significant and because the role of real estate owners has been discussed in a previous section, we only comment on the role of the design group in this context. The following two aspects should especially be emphasized.

Firstly, members of a design group play an important role as experts. The design parameters as well as spatial and technological solutions of a building are selected by the design group. In addition, professional designers make decisions in close co-operation with real estate owners, thus having an opportunity to support their decisions [41]. Secondly, design companies may be willing to profile themselves as supporters of new technology when defining their strategies regarding the sustainability of an energy system.

Thus, to improve their "know-how", also in the case of new technologies, design professionals should be informed about the features of new technologies in a reliable and illustrative way. This could happen for example through seminars, conferences and excursions to pilot buildings.

### 3.5. Interveners

The group "interveners" means members of the "third party" in a situation, when a real estate owner plans to invest in new small-scale CHP technology. Although this interest group does not directly take part in the decision-making of a real estate owner, he or she is very dependent on the decisions of this group, and thus, the role of interveners should be emphasized. On the basis of the literature, we have classified interveners into four categories according to their role in the operational environment. Referring to Table 5, a more detailed description concerning interveners as a part of the operational environment has been presented in Table 9.

The first group of interveners in this context is financiers like bankers (loan) and external investors. Their decisions on whether to allow a loan or not, or whether to invest or not, obviously affect real estate owners' willingness to invest in new technology. There are always risks associated with new technology. On the other hand, the decision of an investor (or banker) is often affected by psychological factors like experience or uncertainty [42]. Thus, the minimization of risks with respect to profitability can be emphasized as the main preference of financiers and investors in the context of CHP. As a consequence, the need has been recognized to study the risk effects of small-scale CHP technology during the life cycle of buildings to provide information for financiers.

Another group of interveners is energy utilities, such as electricity producers, fuel suppliers and grid operators. It is well known that energy production at the building level requires co-operation between a real estate owner and energy utilities, at least at some level [43]. The decisions of energy utilities concerning fuel and electricity pricing as well as investment in new energy infrastructure (e.g. fuel networks) indirectly affect the decisions of real estate owners. Thus, the importance of co-operation between a real estate owner and energy utilities should be emphasized, taking into account the fact that energy utilities can actually be seen as

Table 9
Roles and DM problems of interveners

| Interest group | Role | DM problem type |
|---|---|---|
| Financiers | | |
| Investors | 31, 32, 51 | 23 |
| Bank managers | 31 | 24 |
| Energy utilities | | |
| Electricity producers | 33, 34, 53 | 12, 21 |
| Fuel suppliers | 34, 53, 55 | 12, 21, 25 |
| Grid operators | 53, 55 | 12, 21 |
| Deliverers | | |
| Product manufacturers | 34, 53, 55 | 12, 21, 25 |
| Plant suppliers | 34, 53, 55 | 12, 21, 25 |
| Marketing organizations | 34 | 12, 21 |
| Brokerages | 55 | 12, 21 |
| Insurance business (new aspect) | | |
| Insurers | 35 | 12, 21, 22 |
| Self-insurers | 35 | 12, 21, 22 |
| Risk managers | 35 | 12, 21, 22 |
| Agents | 55 | 12, 21 |

competitors to private energy producers. As a consequence, it is important that new business opportunities be created by the utilities. Technology leasing has been mentioned as an example by Valkiainen et al. [3]. If new, small-scale CHP were to be connected to the electricity grid to feed electricity, it may not affect the stability of the network. New technology is usually complicated when compared with traditional solutions. Thus, business opportunities can also be recognized in the form of various supporting and expert services.

The third group of interveners is deliverers, like product manufacturers, plant suppliers and their market organizations. The obvious belief of deliverers in new technology, their awareness of the features of new technology and its possibilities as an energy source for a building as well as their responsibility for the availability of new technology can be regarded as significant factors also affecting real estate owners' decisions [44]. Their interest is related to the market potential of new technology. The market should be large enough, before manufacturers will be ready to invest in product development and the marketing of new technology. On the other hand, real estate owners are not ready to invest in new technology before it is available at a competitive price. In this situation, a comprehensive search for new business opportunities can also be recommended. The status of deliverers as experts could be utilized in the form of different supporting services. Improved market potential research can also be recommended, dealing with possible locations and building types with respect to issues like assortment of fuels, energy transmission losses and modular flexibility.

Mills [45] presents the insurance business as a new actor in the sector of energy products and services. In the context of CHP, the probability and occurrence of

different hazards is relevant. Risks associated with the safety and reliability of the system can be regarded as the most important risks. Thus, terms of insurance may also affect a real estate owner's decisions.

### 3.6. Public administration

The concept "public administration" can be divided into three groups: authorities, the government and policy makers. On the other hand, each group can be considered at the local (municipal), regional (provincial), national (country) and international (e.g. EU) level when assessing the effects of their decisions on a real estate owner's decisions. Referring to Table 5, a more detailed description concerning public administration as a part of the operational environment has been presented in Table 10.

Authorities usually work as regulatory supervisors in the operational environment and thus they do not directly affect the final decision of a real estate owner. Thinking hypothetically, they can make the realization of a project more difficult, for example by regarding the implementation of a system as contradictory with respect to the regulations. We assume in this context, however, that the laws can be regarded as unambiguous.

The importance of the government and policy makers as a part of the operational environment should be emphasized, because through political decisions the market can be created for new small-scale CHP technologies. Strategic definitions act as a basis for legislation, and by logical extension, regulations. In public policy making, a variety of means can also be utilized to make new technologies more attractive. These so-called "policy instruments" come in many forms and can be divided into legislative and non-legislative measures, as described in Fig. 2.

Table 10
Roles and DM problems of public administration

| Interest group | Role | DM Problem type |
|---|---|---|
| Local administration (municipality) | | |
| Local authorities | 13 | No decisive role |
| Local government | 11 | 11, 12, 23 |
| Local policy makers | 11 | 11, 12 |
| Regional administration (province) | | |
| Regional authorities | 13 | No decisive role |
| Regional government | 11 | 11, 12, 23 |
| Regional policy makers | 11 | 11, 12 |
| National administration (country) | | |
| Authorities | 13 | No decisive role |
| Central government | 12 | 11, 12, 23 |
| National policy makers | 11 | 11, 12 |
| International administration (EU) | | |
| International authorities | 13 | No decisive role |
| International policy makers | 11 | 11, 12 |

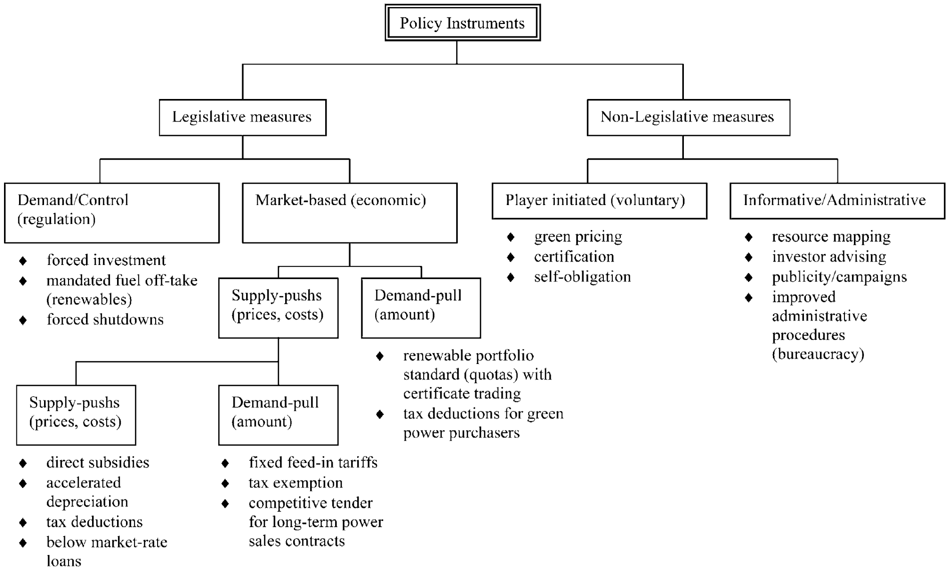



Fig. 2. A typology of policy instruments [34].

According to the synthesis made on the basis of references [46–50], six main sectors of preferences for policy making have been identified with respect to their impact on human health, the environment, infrastructure, society, the national (also regional, international) economy and the features of new technology. In the context of small-scale CHP, the importance of the Kyoto Agreement should be emphasized. For example, in the case of Finland, the starting point of energy policy is the National Energy Strategy, which is also ultimately based on the Kyoto Agreement. The aims of Finnish energy policy are to secure the availability of energy at competitive prices and to keep emissions at a level defined by international agreements. The following actions are thus suggested by the Council of State: [49]

- to decrease the amount of carbon in the energy infrastructure;
- to promote competition and innovations in the energy market;
- to promote efficient use of energy and energy-saving solutions;
- to promote the use of bioenergy and other domestic energy sources;
- to keep energy technology at a high level;
- to ensure versatile and cheap energy production;
- to ensure reliability of the energy sector.

A more detailed and more practical approach can be seen in the building regulations. According to the synthesis made on the basis of references [51–55], many of these regulations in Finland are quite old and do not take into account the possibility of electricity production at building level in the best possible way. In the

future, the new small-scale CHP technologies and their advantages should also be better considered in the regulations, especially with respect to efficiency, acoustics and safety issues.

In spite of many strategic and political definitions in the energy sector, concrete actions, for example in the form of updated regulations and use of ''policy instruments'', are still expected. Because the bureaucracy is often very inflexible, slow, and complicated, the climate for the introduction of new technology may be strongly impaired. To improve the situation, we recommend that co-operation and interaction between policy makers and experts should be improved in the context of small-scale CHP.

### 3.7. Society

In this article, we assume that the concept ''society'' includes all human beings, their activities and preferences that have not been dealt with in Sections 3.2–3.6. On the basis of the literature, we have classified society into seven categories according to the status of these categories in the operational environment: science and education, non-governmental organizations, international organizations, the public at large, industry, mass media and agriculture. It is reasonable to assume that society defined in this way does not directly take part in the decision-making concerning small-scale CHP. Referring to Table 5, a more detailed description concerning society as a part of the operational environment has been presented in Table 11.

Society, however, indirectly affects decisions of almost all the other interest groups. The role of science and education as the original source of all the expertise and information should be emphasized. Their mission is to gradually influence attitudes through education. This process, however, is very slow. Instead, activities of non-governmental organizations (NGOs) [56], international organizations like UN organizations and coalitions (e.g. OPEC, EFTA), and especially the mass media [56], can be regarded as a faster way to change attitudes. If the advantages of small-scale CHP, especially with respect to environmental effects, can be shown in an illustrative way, that can lead to some kind of ''fashion'' or ''trend'' and temporarily have a positive effect on the market. On the other hand, this situation can create public pressure, which in turn affects public policy making in a positive way. The disadvantage is that the change may be temporary and at least it is probably quite unpredictable.

It is worth mentioning that if a private energy producer plans to sell some electricity to the grid, the industry can be seen as a competitor, via its inclination to sell surplus electricity to the grid [43]. The possibility to reduce emissions is the major concern of agriculture, taking into account its role as a life supporter (food producer).

### 3.8. The balance of nature

In the literature, the concepts ''biodiversity'', ''habitat'' and ''ecosystem'' have often been used to describe the role of nature as a life support system for all

Table 11
Roles of the society

| Interest group | Role |
|---|---|
| Science and education | |
| Scientists | 46, 47, 48, 49, 53 |
| Teachers | 53, 410 |
| Researchers | 46, 47, 49, 53, 55, 410 |
| Academic institutions | 46, 47, 49, 53, 410 |
| Technical institutions | 46, 47, 49, 53, 55, 410 |
| Non-governmental organizations | |
| Associations | 46, 47, 49, 48 |
| Trade organizations | 46 |
| Consumer-interest organizations | 48 |
| Environmental groups | 49 |
| Religious organizations | 47, 48, 49 |
| International organizations | |
| UN organizations | 46, 47, 49, 48 |
| International coalitions (EFTA, OPEC, NATO) | 46, 48 |
| The public at large | |
| Citizens | 45 |
| Tourists | 45 |
| Industry | 31, 33, 34, 44, 55 |
| Mass media | 46, 47, 48, 49, 410 |
| Agriculture | 44, 411 |

human beings, plants and animals. Thus, nature is the ultimate factor in the operational environment. It is evident that the demands of nature are strongly associated with environmental effects, which are usually regarded as occurring in the form of harmful emissions. The consequences of these emissions, in turn, will cause global warming, pollution, acidification, ozone depletion and deforestation. Destruction of habitats and species, changes in biodiversity, modification of surroundings and spoiling of the landscape should also be dealt with when evaluating the environmental effects of energy production by means of new technology. It is obvious, that as a part of nature, human beings will have to carry the consequences of bad decisions in the future: for example, natural disasters caused by climate change. Thus, we always recommend the use of new, environmental friendly technologies, taking into account, however, that in northern regions climate change may have some positive effects: for example, increased harvests and savings in the required amount of heating energy.

When considering small-scale CHP technologies as a source of energy in the context of buildings, flexibility with respect to fuels and the efficiency of new technologies should first be emphasized as an answer to the question concerning harmful emissions. In the short term, the amount of toxic emissions can be decreased by using environmental friendly fuels. In the long term, even the elimination of almost all harmful emissions may be possible, related to the vision of hydrogen economy. Secondly, applying distributed energy production associated with optimal

integration into buildings can be regarded as an alternative to new, large power plants. Thus, such environmental effects like destruction of habitats and species, changes in biodiversity, modification of surroundings and spoiling of the landscape can be decreased.

The best way to increase knowledge about the environmental effects of small-scale CHP in buildings seems to be by connecting environmental values to life-cycle assessments. Another interesting way of handling ecological effects is described by Stöglehner [39], where the concept of the "ecological footprint" is introduced to define the land exploitation for an amount of energy produced by a new technology compared to that for an amount of energy produced by fossil fuels.

## 4. Possibilities of small-scale CHP in buildings

### 4.1. Summary of small-scale CHP technologies

At this moment, the most important competing technologies in the field of small-scale CHP are reciprocating engines, micro-turbines (electric power under 250 kW), Stirling engines, and fuel cells. In general, the technical features of small-scale CHP technologies are well-documented, for example by Vanhanen [2], Valkiainen [3] and Ellis [43]. Because of the novelty of the technology in this field of application, however, operational experiences for extended periods have not been available so far. On the other hand, competitive actors have been unwilling to publish the results of their studies. Thus, many uncertainties are still associated with information concerning small-scale CHP technologies. In this section, a brief review is presented concerning different CHP technologies. From the point of view of sustainability, fuel cells are almost transcendent. Thus, this technology is considered a bit more at length than the competing technologies. Some of the features of these technologies have been listed in Table 12.

#### 4.1.1. Reciprocating engines

A power plant based on a reciprocating engine simply consists of a reciprocating engine (diesel, gas, or multiple fuel) and a generator linked to the engine. Typical of this kind of plant is its quite high electrical efficiency, a large power range and a versatile assortment of fuels. Usually, reciprocating engines use natural gas or diesel oil as fuels, but the use of bio-oils and even regenerative biomass is also under research. Engine-based plants are usually delivered as standard modules, which makes them flexible and attractive for use in quite different applications. The applicability of gas engines is at its best in back-up systems, whereas diesel engines are recommended for continuous use.

Owing to moving parts, the engines need service regularly. In addition, they are noisy and thus not very attractive alternatives for residential applications. Another drawback is their emissions. $CO_2$ and $SO_2$ emissions are strongly dependent on the fuel used. The amounts of $NO_x$, CO and incombustible hydrocarbons in exhaust gases also depend on other conditions of combustion, like the temperature and the

Table 12
Technical features of small-scale CHP devices [2, 3, 43, 57]

| | Reciprocating engines | Micro-turbines | Stirling engines | PEM fuel cells |
|---|---|---|---|---|
| Electrical power (kW) | 10–200 | 25–250 | 2–50 | 2–200 |
| Electrical efficiency, full load (%) | 25–45 | 25–30 | 15–35 | 40 |
| Electrical efficiency, half-load (%) | 23–40 | 20–25 | =35 [11] | 40 |
| Total efficiency (%) | 75–85 | 75–85 | 75–85 | 75–85 |
| Electrical power/heat flow (–) | 0.5–1.1 | 0.5–0.6 | 0.3–0.7 | 0.9–1.1 |
| Output temperature level (°C) | 85–100 | 85–100 | 60–80 | 60–80 |
| Fuel | Natural or biogas, diesel, fuel oil | Natural or biogas, diesel, gasoline, alcohols | Natural or biogas, LPG, several liquid or solid fuels | Hydrogen, gases including hydrogen, methanol |
| Length of maintenance cycle (h) | 5000–20 000 | 20 000–30 000 | ≈5000 | [a] |
| Investment costs (US$/electrical kW) | 800–1500 | 900–1500 | 1300–2000 | 2500–3500 |
| Maintenance costs (¢/electrical kW) | 1.2–2.0 | 0.5–1.5 | 1.5–2.5 | 1.0–3.0 |

[a] No experiences available.

amount of air. Plants based on reciprocating engines are best applicable to buildings with smooth electricity and heat consumption profiles. The larger the size, the greater the benefits [2, 3].

#### 4.1.2. *Micro-turbines*

The concept ‘‘micro-turbines’’ usually means gas turbines with electrical power generation from 25 to 250 kW. In general, a plant consists of a generator, a compressor, a combustion chamber, and a turbine connected to each by a shaft. Air is conducted to the combustion chamber via a compressor and usually a recuperator, in which the heat of exhaust gases is recovered. Because of the high frequency of the alternating current produced by the generator, a rectifier and a transformer are also needed to produce electricity suitable for electrical devices (in Finland: 220 VAC, 50 Hz).

Typical of micro-turbine plants are quite low noise and vibration due to their low weight and high rotation speed. Because of their small size, the space requirement is also of minor concern. The high exhaust gas outlet temperature range (450–550 °C) makes them attractive for heat recovery and production. A drawback is low electrical efficiency, especially on part load. The price of the technology and service costs are also high. From the point of view of emissions, micro-turbines are a little bit more environmentally friendly than, for example, reciprocating engines. Especially, their $NO_x$ emissions are lower.

Natural gas and various liquid fuels (diesel oil, gasoline, methanol, ethanol, etc.) are suitable for micro-turbines. Gas turbines are best applicable to processes with a need for high temperatures (e.g. steam production). In contrast, their applicability for residential purposes is poor because they are expensive and inflexible to load changes [2, 3].

#### 4.1.3. Stirling engines

The Stirling engine is a reciprocating engine. Contrary to conventional diesel and gas engines, however, its cylinder is closed and combustion takes place outside of the cylinder. The piston moves in the cylinder because of compression or expansion of the working gas (helium, hydrogen) due to the alternating heating and cooling of the cylinder by means of external combustion.

Typical of Stirling engines are their rather low emissions (especially $NO_x$) and lower noise production than is the case in conventional reciprocating engines. External combustion also causes a decreased need for servicing despite the fact that the maintenance cycle time period is in the same class as for the other reciprocating engines. Due to its external combustion, various fuels are also suitable. An interesting fuel alternative is biomass. A drawback is the rather low electrical efficiency, about 25–30% when natural gas is used as a fuel. When solid fuels (e.g. biomass) are used, the efficiency can be as low as 15%. The total efficiency, however, is not significantly lower than that of other CHP applications.

Stirling engines are very applicable to residential buildings, especially because the electricity/heat ratio is suitable. Their low efficiency, however, supports their use as backup power supplies rather than one in continuous use [2, 3].

#### 4.1.4. Fuel cells

A fuel cell produces electricity electrochemically, by combining hydrogen and atmospheric oxygen. At its simplest, the fuel cell consists of an anode, a cathode, and an electrolyte. The fuel, hydrogen, releases electrons on the anode, which are then conducted to the cathode via an external circuit. The hydrogen ions (protons) then diffuse directly through the electrolyte material to the cathode, and are then converted to water by reduction with the oxygen of the air. The rapidity of the reaction depends on both the electrolyte and the catalyst material used on the surfaces of the anode and the cathode. The reaction can also be made more intense by heating the process (e.g. by external combustion) and thereby increasing the temperature at which it takes place. Fuel cells are usually classified into different types according to electrolyte, operational temperature and source of hydrogen. If the fuel is not available as pure hydrogen, it can be released from various fuels by means of a reformation process. In Table 13, some existing fuel cell types have been presented.

There are many factors that make fuel cells beneficial. The most frequently mentioned benefit is its electrical efficiency, which can be up to 45–55%. Reformation of fuel decreases the efficiency, but an efficiency of approximately 40% is still achieved. On the other hand, the higher the temperature, the better the efficiency. In addition, the electrical efficiency of fuel cells is both quite immune to load

Table 13
Existing fuel cell technologies [58]

| Type | Electrolyte | Operational temperature (°C) | Source of hydrogen |
|---|---|---|---|
| Alkaline fuel cells (AFCs) | Potassium hydroxide | 50–200 | Clean hydrogen or hydrazine |
| Direct methanol fuel cells (DMFCs) | Polymer | 60–200 | Liquid methanol |
| Phosphoric acid fuel cells (PAFCs) | Phosphoric acid | 160–210 | Hydrocarbons or alcohols |
| Sulphuric acid fuel cells (SAFCs) | Sulphuric acid | 80–90 | Alcohols or uncleaned hydrogen |
| Proton exchange membrane fuel cells (PEMs) | Polymeric membrane | 50–80 | Hydrocarbons or methanol |
| Molten carbonate fuel cells (MCFCs) | Nitrate, sulphate or carbonate in molten condition | 630–650 | Clean hydrogen, natural gas, propane, diesel |
| Solid oxide fuel cells (SOFCs) | Solid ceramic material | 600–1000 | Natural gas or propane |
| Solid polymer fuel cells (SPFCs) | Solid polystyrene | 80–90 | clean hydrogen |

changes and not power range dependent. Another benefit is its very low emission rate. If pure hydrogen is used, the only emission is water. If reformation is used, $CO_2$ and a minimal amount of oxides of sulphur and nitrogen is formed, depending on the fuel. Other benefits are noiselessness, reliability, modularity, and rapid adaptability to load changes. The most important drawback is the investment cost. At the moment, fuel cell plant costs can be even three times higher compared to those of reciprocating engines. Another problem is that fuel cells are more demanding in respect of fuel production, storage, and transportation than other technologies. Dunn [5] presents a review concerning these problems. At the moment, however, these methods seem to be more or less conceptual and still not applicable to construction in practice. The benefits and drawbacks also depend on the type of the fuel cell, as is presented in Table 14.

Fuel cells are applicable for various purposes, mainly because of their load- and size-independent electric efficiency. The suitability, of course, depends somewhat on the type of the fuel cell. For example, the operational temperature level is one example of a limiting factor. The fuel cell is equally suited for both continuous and backup uses. However, due to the high price of the technology, this application may not yet be feasible.

### *4.2. Small-scale CHP from the point of view of buildings*

In this section, we briefly consider the requirements set for a small-scale CHP by a building. They are a matter of deep interest, especially when a device representing new technology is to be applied to an existing building in an upgrading project. Although different types of buildings differ strongly from one another, a basic common requirement for building energy production is the ability to satisfy the

Table 14
Benefits and drawbacks of different fuel cell types [58–60]

| Type | Benefits | Drawbacks |
|---|---|---|
| Alkaline fuel cells (AFCs) | No expensive platinum catalysts | Requires $CO_2$ cleaning system |
| Direct methanol fuel cells (DMFCs) | Like PEM<br>Easy to store liquid methanol<br>Reformer integrated | Like PEM |
| Phosphoric acid fuel cells (PAFCs) | Good total efficiency | Expensive platinum catalysts<br>Low power density |
| Proton exchange membrane fuel cells (PEMs) | Good performance<br>Rapid starting<br>Adaptability to load changes<br>Limited corrosion<br>Easy to use solid electrolyte | Expensive platinum catalysts (due to low temperature) |
| Molten carbonate fuel cells (MCFCs) | Good total efficiency<br>Low catalyst requirements<br>Many fuels suitable | Corrosion of electrolyte<br>Cathode needs $CO_2$ continuously |
| Solid oxide fuel cells (SOFCs) | Solid electrolyte<br>No corrosion<br>Simple | High operational temperature<br>Short lifetime<br>Expensive materials |
| Solid polymer fuel cells (SPFCs) | Easy to use<br>High power density<br>Not sensitive to operational environment | Costs<br>Only clean hydrogen suitable as fuel |

electricity and heat demands of the building. Because the technology-specific ratio of produced electricity to produced heat cannot be significantly adjusted during operation, it should be comparable with the building-specific ratio of demanded electricity to demanded heat. Correspondingly, the outlet temperature level should be suitable for heat production. The minimum required temperatures in building applications vary from 40 °C (floor heating) to 80 °C (radiator heating). Thus, a temperature of approximately 100 °C can be regarded as the sufficient output temperature of a CHP system. Once these conditions are satisfied, optimal operation becomes possible and the need for additional energy from external sources is minimal. However, feasible operation usually requires the co-operation of the energy utility to cope with a shortage or surplus of energy. More about such co-operation is written, for example by Ellis [43].

Another requirement is to satisfy the electricity and heat demand at varying load conditions. The energy demand profile of a building is characterized periodically by unpredictability. Thus, a short response time is demanded. On the other hand, a good part-load efficiency imparts a good energy cost feasibility profile to the system. In some cases (e.g. hospitals), reliability is a very significant requirement [43].

### *4.3. Suitability of small-scale CHP for different building types*

The following eight criteria have been mentioned by Vanhanen [2] and Valkiainen [3] to evaluate the applicability of small-scale CHP technologies in buildings:

- electrical efficiency;
- length of life cycle of a technology;
- space demanded to install a technology in a building;
- emissions;
- flexibility of control (in practice: response time);
- availability of fuel in the short term;
- level of noise generated (loudness);
- costs.

The performance of each technology has been evaluated and transcribed on a scale of 1 (poor) to 5 (excellent) and illustrated by star diagrams, as shown in Fig. 3. These estimations, however, have to be viewed with a critical eye, because of their general, approximate nature, and insufficient, even contradictory, knowledge regarding how the technologies function in real buildings over an extended period of time. A couple of examples can easily be taken to illustrate misleading factors associated with these figures. Firstly, the length of the life cycle is relatively short at the moment, at least for new technologies in the smallest class, due to the state-of-the-art of product development. Secondly, the new technologies have not yet achieved the level of development at which their environmental friendliness is at its maximum. For example, although fuel cells are usually mentioned to be almost noiseless, in practice, there are necessary components like air compressors and water pumps that make an actual fuel cell CHP application quite noisy. Thus, these figures more likely indicate the situation in the future than that at this moment.

As a consequence of factors presented in Sections 4.1 and 4.2 and those listed previously, the conclusion can be drawn that some small-scale CHP technologies are more suitable for a certain type of building application than others. Table 15 roughly illustrates the technical compatibility of CHP technologies and different building types by means of an assessment based on the features of the technologies and the different requirements of the building types. The more the plus points, the better the suitability. The more the negative points, the worse the suitability.

## 5. Conclusions

In the literature, the breakthrough of new, sustainable small-scale CHP technologies is often regarded simply as a matter of decision-making. This article is a review of issues that influence decisions when considering small-scale CHP as an alternative energy source for buildings, especially from the point of view of a real estate owner. On the basis of the literature, the conclusion can be made that the

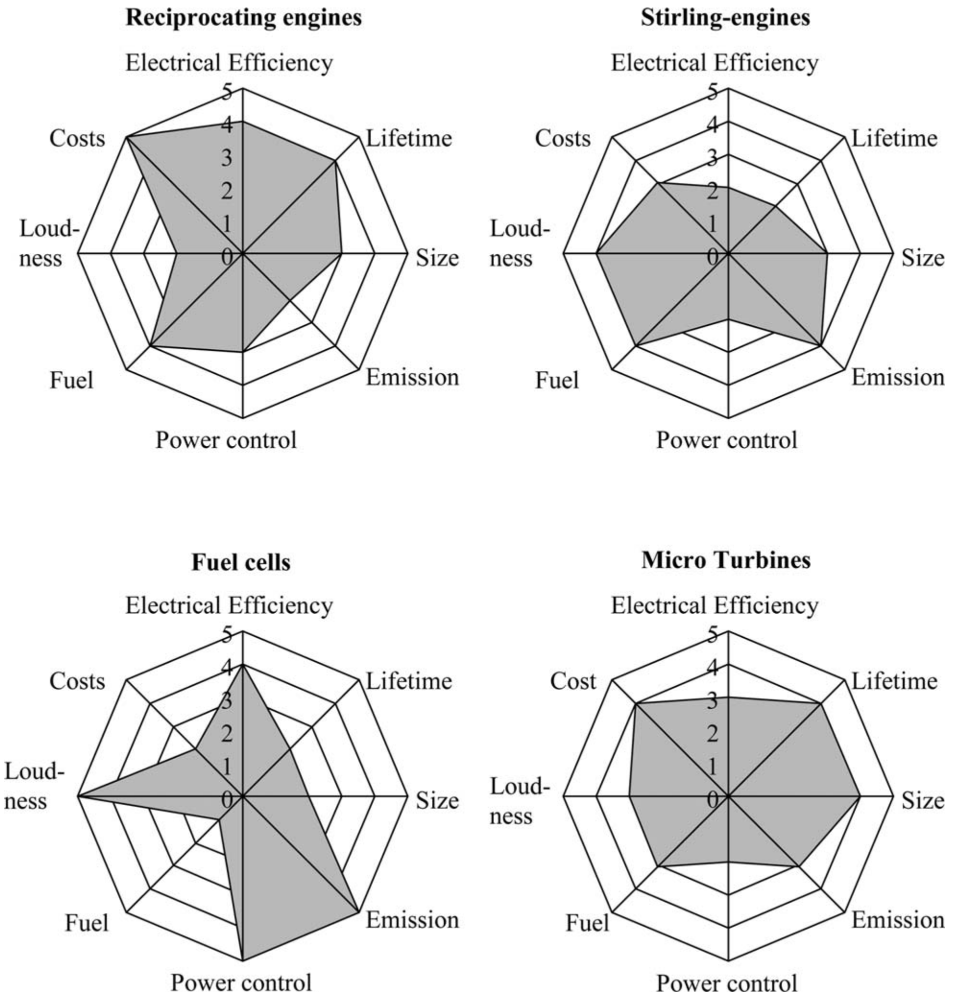



Fig. 3. Performance of small-scale CHP technologies illustrated by star diagrams [2].

Table 15
Technical compatibility of CHP technologies and different building types [2]

| Building type | Reciprocating engines | Gas (micro-) turbines | Stirling engines | Fuel cells |
|---|---|---|---|---|
| Detached house | − | −− | ++ | ++ |
| Row of houses | + | − | ++ | ++ |
| Block of flats | + | − | + | + |
| Office building | + | − | − | + |
| Service building[a] | ++ | − | − | + |
| Industrial building | ++ | ++ | −− | + |

[a] Hotels, hospitals, etc.

following issues in the operational environment mainly affect the willingness of a real estate owner to invest in new small-scale CHP technology:

- the availability of technology and (sustainable) fuels at a competitive price;
- the availability of sufficient amount of reliable information on the advantages and disadvantages of the technology;
- sufficient societal-derived incentives (taxes, subsidies)
- flexibility and technical integrability of the new technology with the building in the form of utilization of waste heat (or surplus electricity) and reliability
- location of the building (remote areas are favorable for small-scale CHP).

To satisfy these conditions, a lot of decisions have to be made by various decision-makers. Their decisions, in turn, are associated with attitudes. To improve the prospects of new technologies in the market, attitudes should be influenced through education, consultation and campaigns. Roughly, the change in attitudes should occur in two phases. In the first phase, public administration should be convinced about CHP, when they are in the process of defining energy policy and laws. The status of public administration as an opinion-former could then be utilized in the most effective way. In the second phase, when new technology arrives on the market in the form of new products, individual real estate owners as well as designers should be equipped with an adequate amount of information concerning sustainable CHP technology. In this study, we thus emphasize that the change in attitudes is strongly associated with information about CHP technology to the right people at the right moment.

In the future, our research will concentrate on recognizing the most feasible techno-economic solutions in the field of small-scale CHP during the life cycle of a building. Because of the novelty of the technology in this field of application, operational experiences for extended periods have not been available so far. Thus, a predictive life-cycle analysis will be applied, taking into account uncertainties by means of sensitivity analysis.

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